

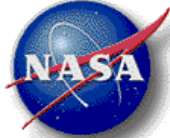
Space Fission Power and Propulsion



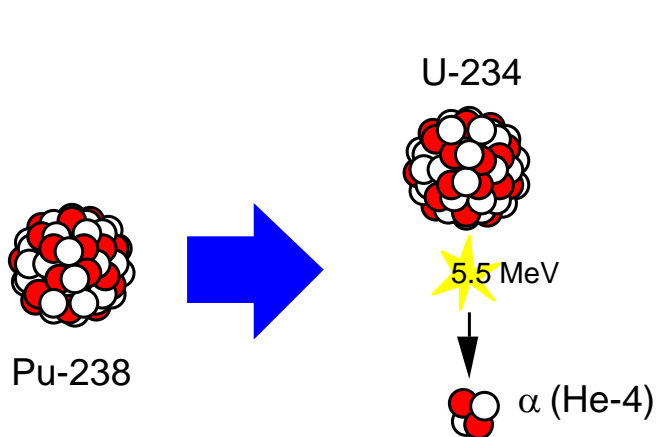
presented by

Mike Houts

Michael.houts@nasa.gov



Basics of Nuclear Systems



Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)

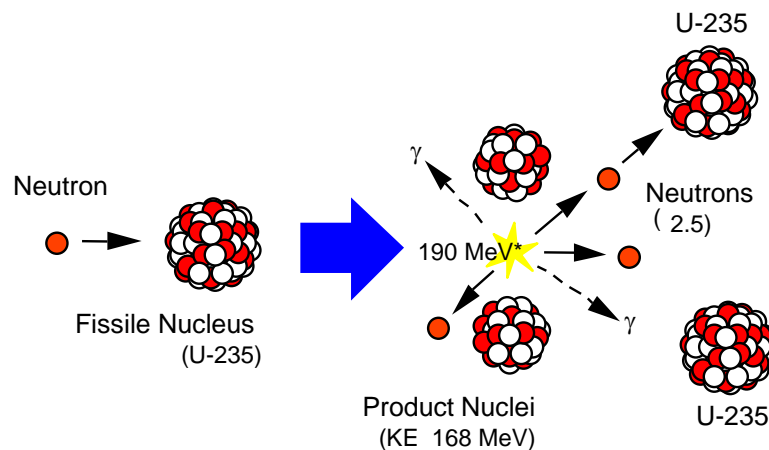
Natural decay rate (87.7-year half-life)

Long history of use on Apollo and space science missions

44 RTGs and hundreds of RHUs launched by U.S. since the 1960s

Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)

Used for both thermal management and electricity production



Heat Energy = 0.851 MeV/nucleon

Controllable reaction rate (variable power levels)

Used terrestrially for over 70 years

Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal

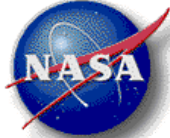
One US space reactor (SNAP-10A) flown (1965)

Former U.S.S.R. flew 33 space reactors

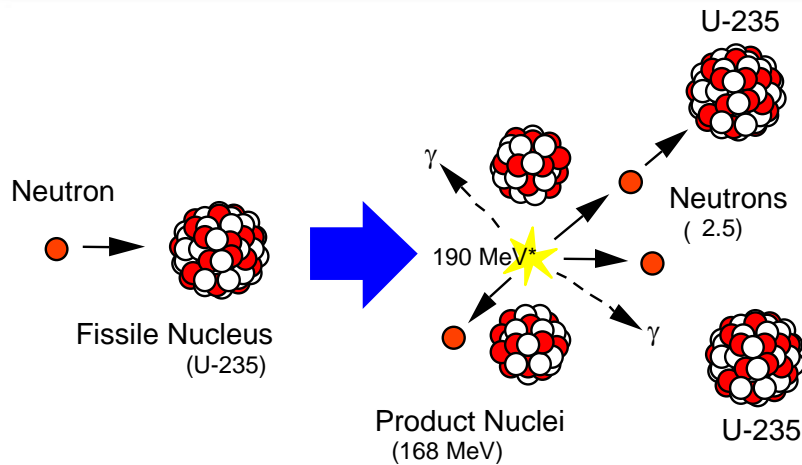
Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)

At steady-state, 1 of the 2 to 3 neutrons released in the reaction causes a subsequent fission in a "chain reaction" process

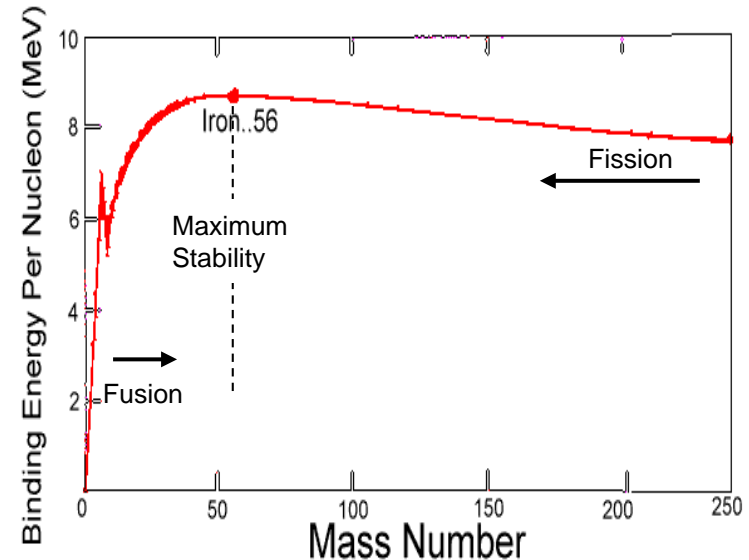
Heat converted to electricity, or used directly to heat a propellant



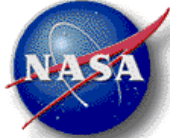
Nuclear Fission Process



180 MeV prompt useful energy (plus 10 MeV neutrinos) - additional energy released in form of fission product beta particles, gamma rays, neutron capture gammas (~200 MeV total useful)

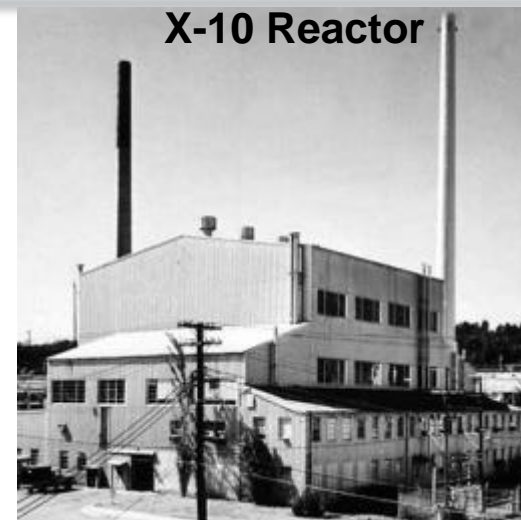


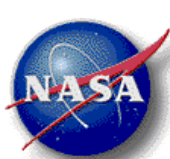
- Neutron absorbed by heavy nucleus, which splits to form products with higher binding energy per nucleon. Difference between initial and final masses = prompt energy released (190 MeV).
 - *Fissile* isotopes (U-233, U-235 and Pu-239) fission at any neutron energy
 - Other actinides (U-238) fission at only high neutron energies
- Fission fragment kinetic energy (168 MeV), instantaneous gamma energy (7 MeV), fission neutron kinetic energy (5 MeV), Beta particles from fission products (7 MeV), Gamma rays from fission products (6 MeV), Gamma rays from neutron capture (~7 MeV).
- For steady power production, 1 of the 2 to 3 neutrons from each reaction must cause a subsequent fission in a *chain reaction* process.



Fission Introduction

- **Creating a fission chain reaction is conceptually simple**
 - Requires right materials in right geometry
- **Good engineering needed to create safe, affordable, useful fission systems**
- **1938 *Fission Discovered***
- **1939 *Einstein letter to Roosevelt***
- **1942 *Manhattan project initiated***
- **1942 *First sustained fission chain reaction (CP-1)***
- **1943 *X-10 Reactor (ORNL), 3500 kWt***
- **1944 *B-Reactor (Hanford), 250,000 kWt***
- **1944-now *Thousands of reactors at various power levels***





Fission is Highly Versatile with Many Applications

- Small research reactors
 - Examples include 2000 kWt TRIGA reactor recently installed in Morocco (< \$100M)
- Advanced, high-power research reactors and associated facilities
 - Examples include the US Fast Flux Test, EBR-II, ATR, HFIR
- Commercial Light Water Reactors
1,371,000 kWe (3,800,000 kWt)
- Space reactors
 - SNAP-10A 42 kWt / 0.6 kWe
 - Soviet reactors typically 100 kWt / 3 kWe (some systems >150 kWt)
 - Cost is design-dependent



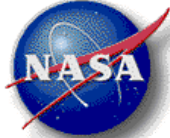
Figure II-92. SNAP 10A Flight System



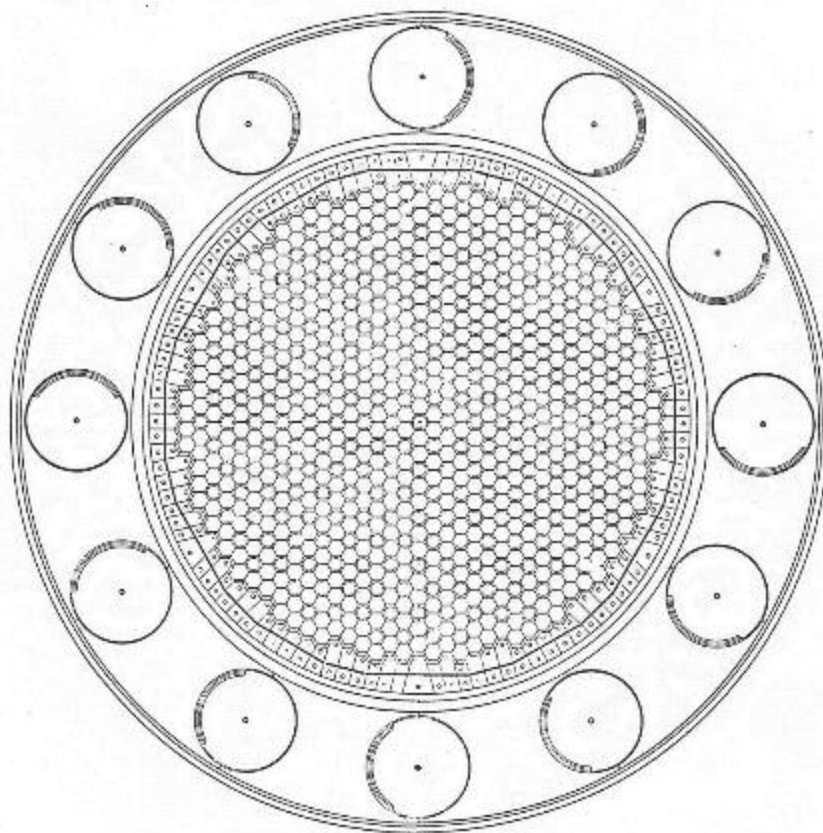
Fission is Highly Versatile with Many Applications (continued)

- Naval Reactors
 - Hundreds of submarines and surface ships worldwide
- Production of medical and other isotopes
- Fission Surface Power
 - Safe, abundant, cost effective power on the moon or Mars
- Nuclear Thermal Propulsion
 - Potential for fast, efficient transportation throughout inner solar system
- Nuclear Electric Propulsion
 - Potential for efficient transportation throughout solar system
- Highly advanced fission systems for solar system exploration





Typical Space Fission System Operation



~1.0 m

System power controlled by neutron balance

Average 2.5 neutrons produced per fission

– Including delayed

Constant power if 1.0 of those neutrons goes on to cause another fission

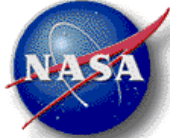
Decreasing power if < 1.0 neutron causes another fission, increasing if > 1.0

System controlled by passively and actively controlling fraction of neutrons that escape or are captured

Natural feedback enables straightforward control, constant temperature operation

200 kWt system burns 1 kg uranium every 13 yrs

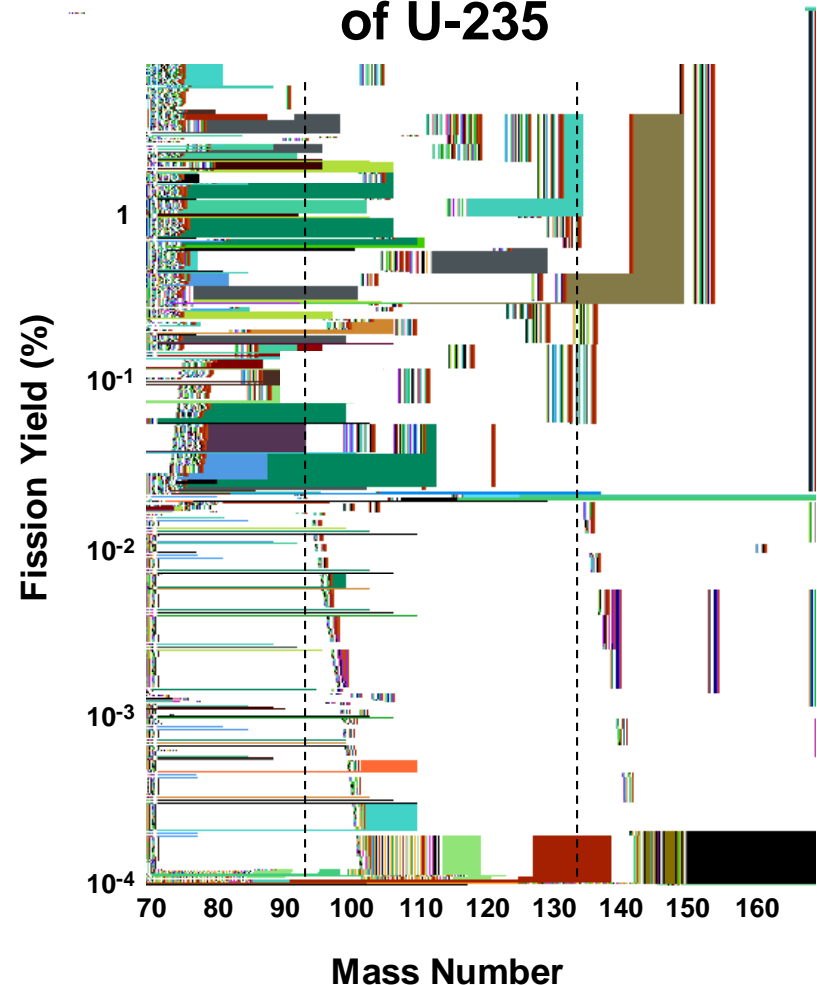
- **45 grams per 1000 MW-hr**

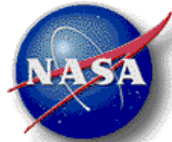


Fission Products

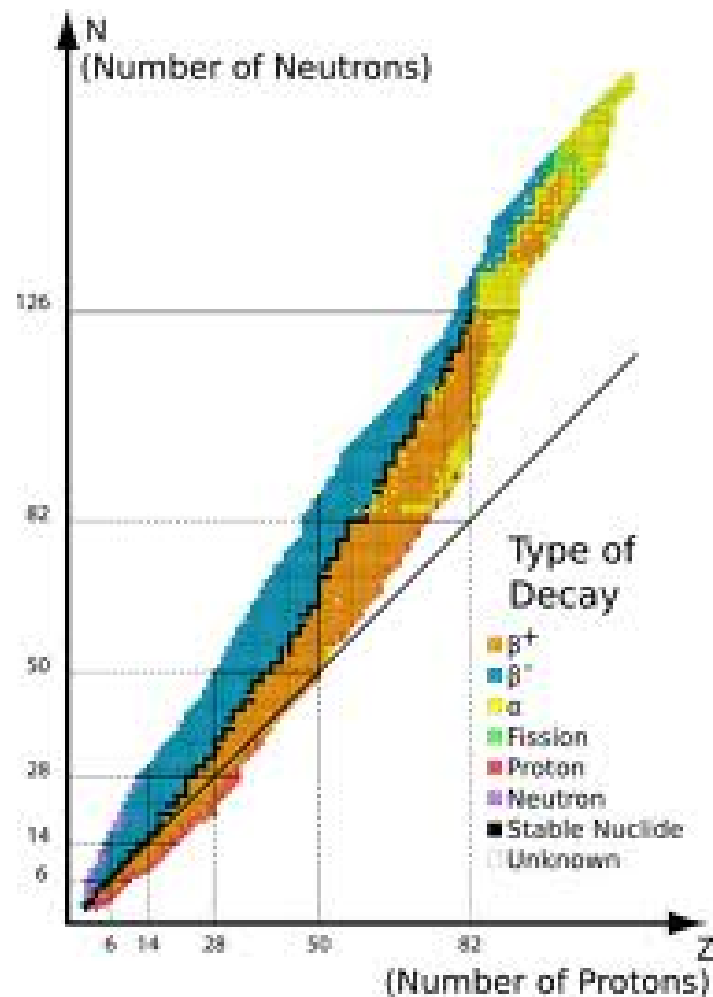
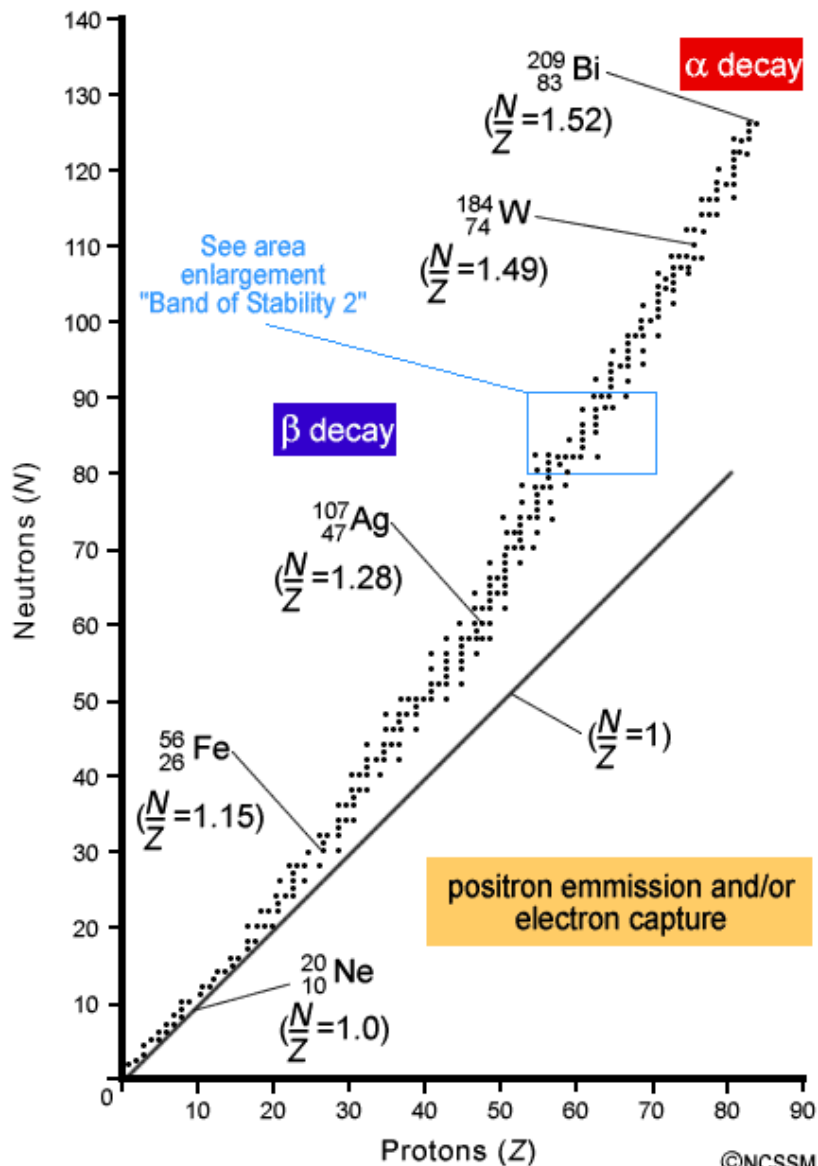
- Fission events yield bimodal distribution of product elements.
- These products are generally neutron-rich isotopes and emit beta and gamma particles in radioactive decay chains.
- Most products rapidly decay to stable forms – a few, however, decay at slow rates or decay to daughter products which have long decay times.
- Example fission products of concern:
 - Strontium-90 (28.8-year half-life)
 - Cesium-137 (30.1-year half-life)
- Isotope amounts decrease by factor of 1,000 after 10 half-lives and 1,000,000 after 20 half-lives.
- Decay power 6.2% at $t=0$ (plus fission from delayed neutrons), 1.3% at 1 hour, 0.1% at 2 months (following 5 years operation).

Product Yields for Thermal Neutron (0.025 eV) Fission of U-235





Fission Products





Gamma Radiation Shielding

$$I/I_0 = (B)e^{-\mu/\rho(x\rho)}$$

I = intensity

I_0 = initial intensity

B = Buildup Factor

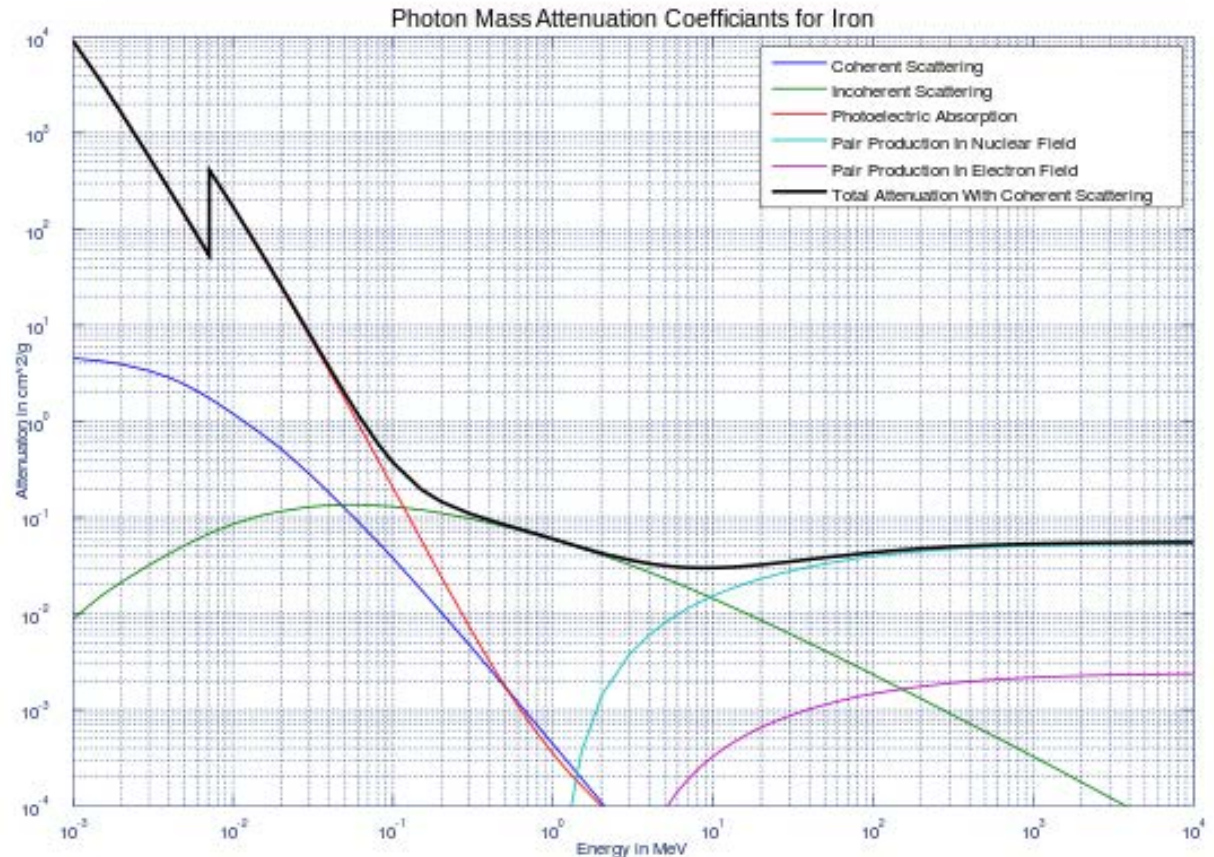
e = 2.71828

μ = linear attenuation coefficient

ρ = density

μ/ρ = mass attenuation coefficient

X = shield thickness

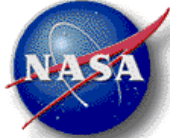




Mass Attenuation Coefficient (μ/ρ cm²/g) of Al, Fe, W, and U at 1.0, 3.0, and 8.0 MeV

	Al	Fe	W	U
1.0 MeV	0.0615	0.0600	0.0618	0.0790
3.0 MeV	0.0354	0.0362	0.0408	0.0445
8.0 MeV	0.0244	0.0299	0.0447	0.0488

Shield design must also take into account “buildup”, inelastic neutron scatter, gammas from neutron capture, geometry, thermal management, radiation damage, and other factors.



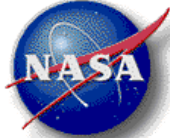
Neutron Radiation Shielding

Use hydrogenous material to slow neutrons.

Optimal Design – Avoid Capture Gammas, Gammas From Inelastic Scatter

^6Li and ^{10}B capture neutrons with no significant gamma radiation released.

Water is a great neutron shield, borated water a little better still!



Neutron Cross Sections

Measure of the probability of a particular neutron-nucleus interaction.

Property of the nucleus and the energy of the incident neutron.

Symbolized “ σ ”, common unit is “barn” = $1.0 \times 10^{-28} \text{ m}^2$

Neutron Flux = $n v = \Phi$

n = neutrons / m^3

v = neutron speed (m/s)

Reaction rate = $\Phi N \sigma$

N = nuclei / m^3

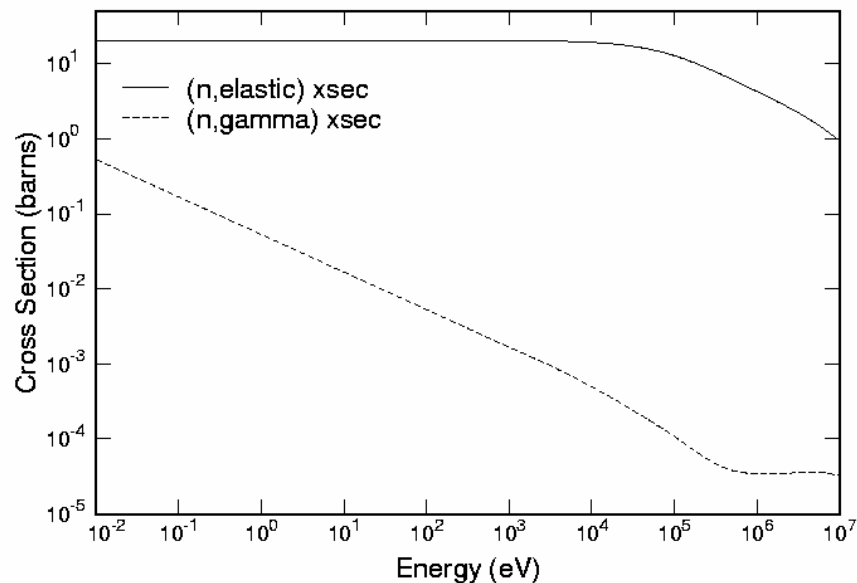
Φ = neutron flux (neutrons / $\text{m}^2\text{-s}$)

σ = cross section (m^2)

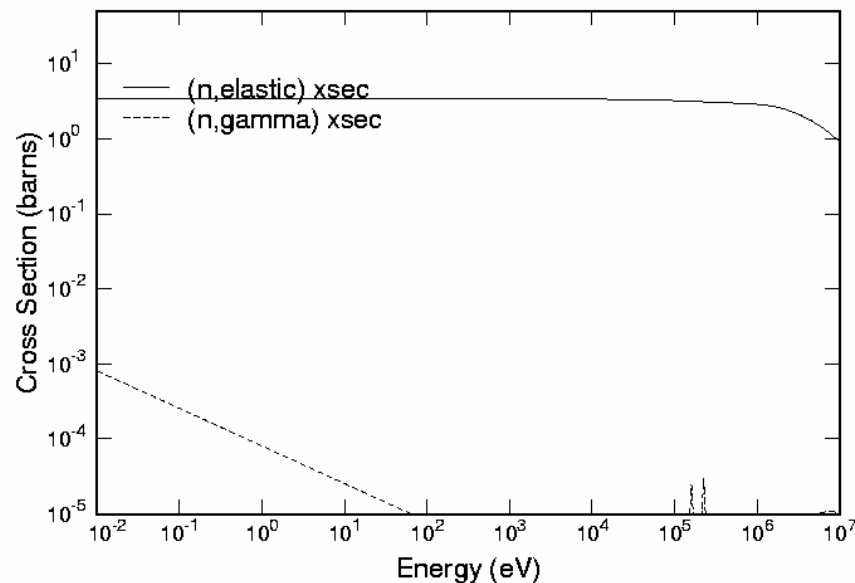


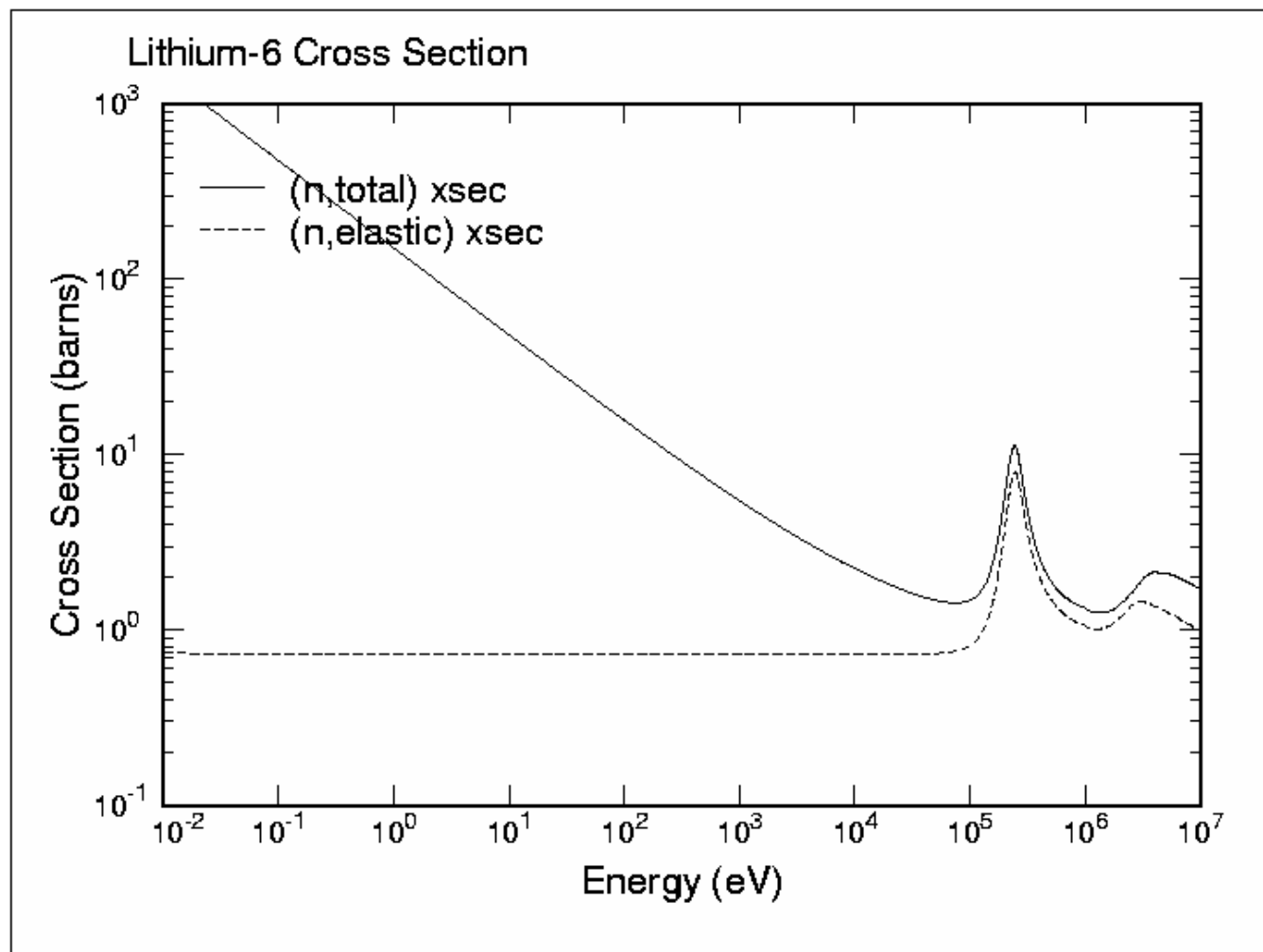
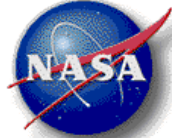
Comparison of Hydrogen and Deuterium Cross Sections

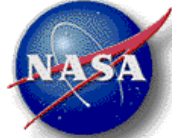
Hydrogen Energy Dependent Neutron Cross Sections



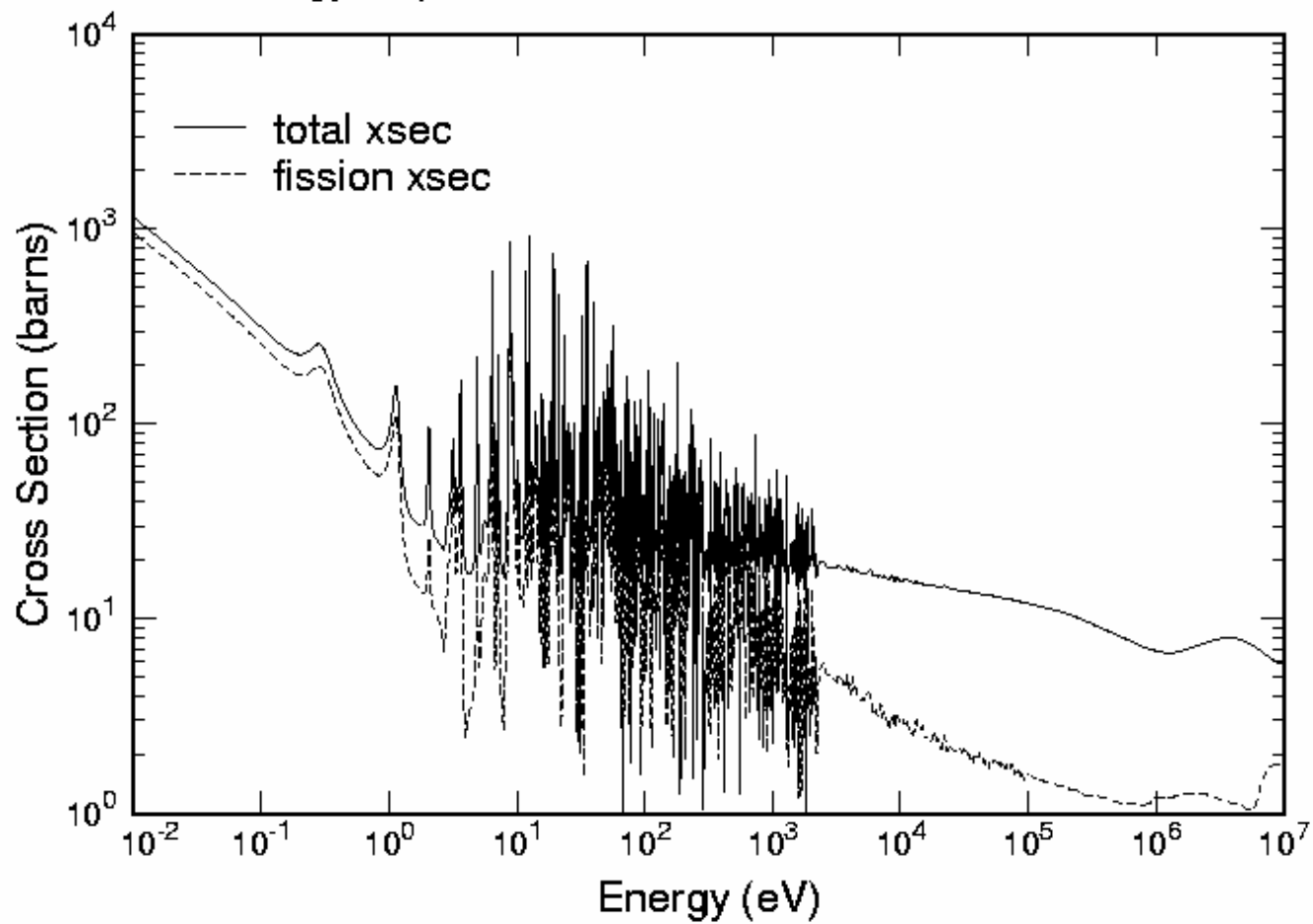
Deuterium Energy-Dependent Cross Sections

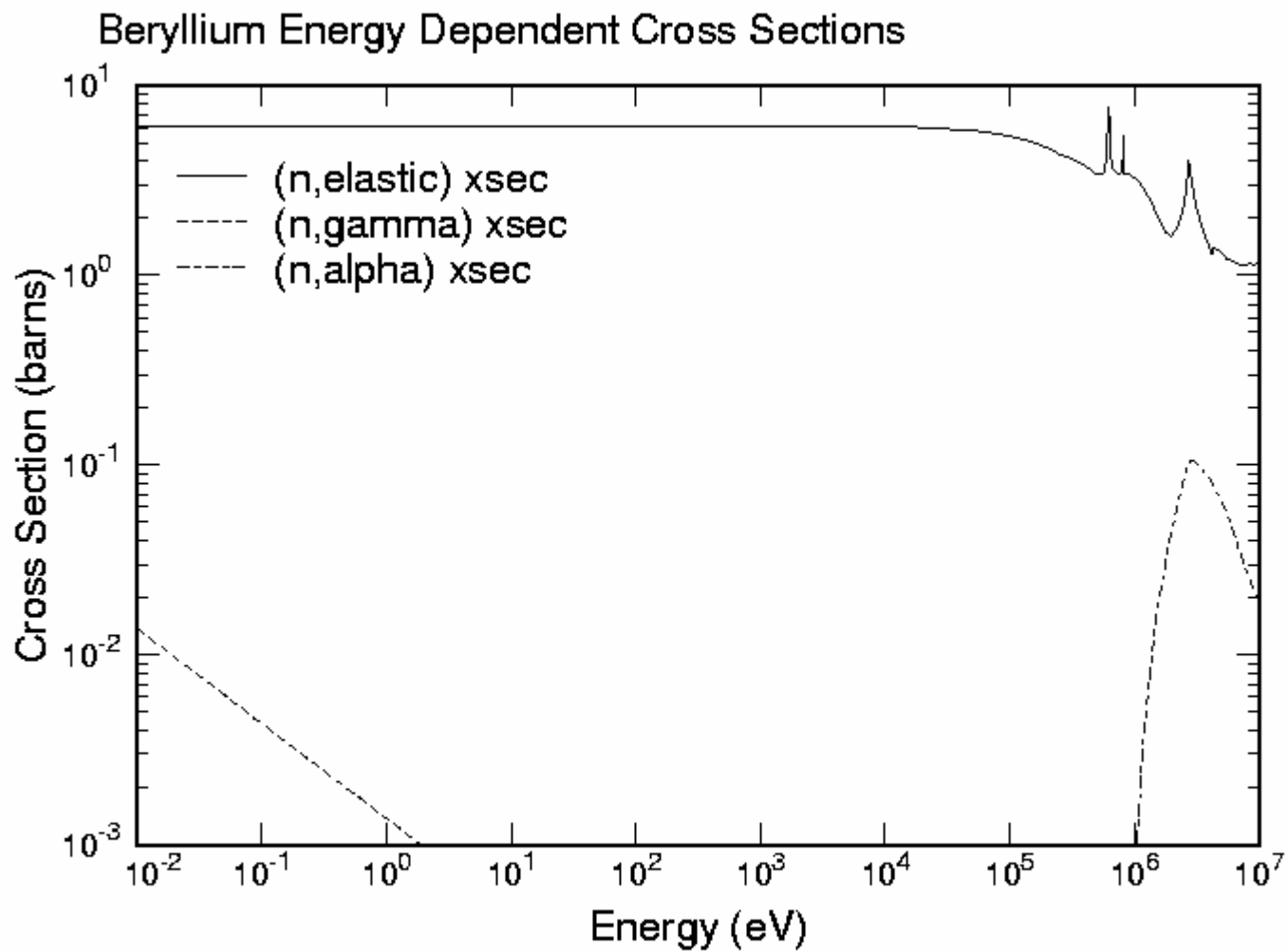
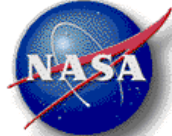


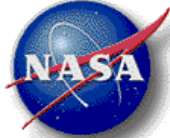




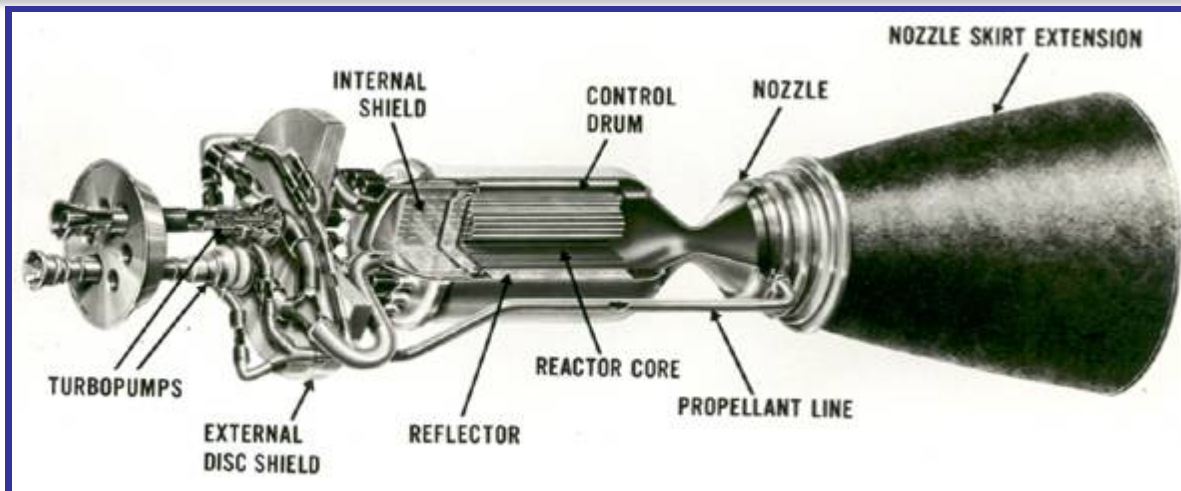
U-235 Energy Dependent Cross Sections







Nuclear Thermal Propulsion (NTP) Enhances or Enables Advanced Space Missions, Including Human Mars Missions



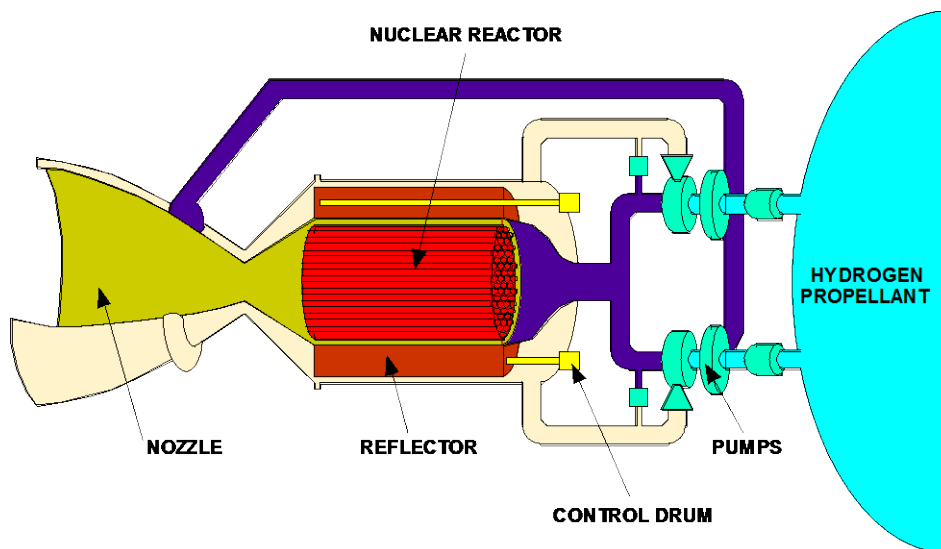
- Nuclear thermal propulsion (NTP) is a fundamentally new capability
 - Energy comes from fission, not chemical reactions
 - Virtually unlimited energy density
- Initial systems will have specific impulses roughly twice that of the best chemical systems
 - Reduced propellant (launch) requirements, reduced trip time
 - Beneficial to near-term/far-term missions currently under consideration
- Advanced nuclear propulsion systems could have extremely high performance and unique capabilities
- First generation NTP could serve as the “DC-3” of space fission power and propulsion



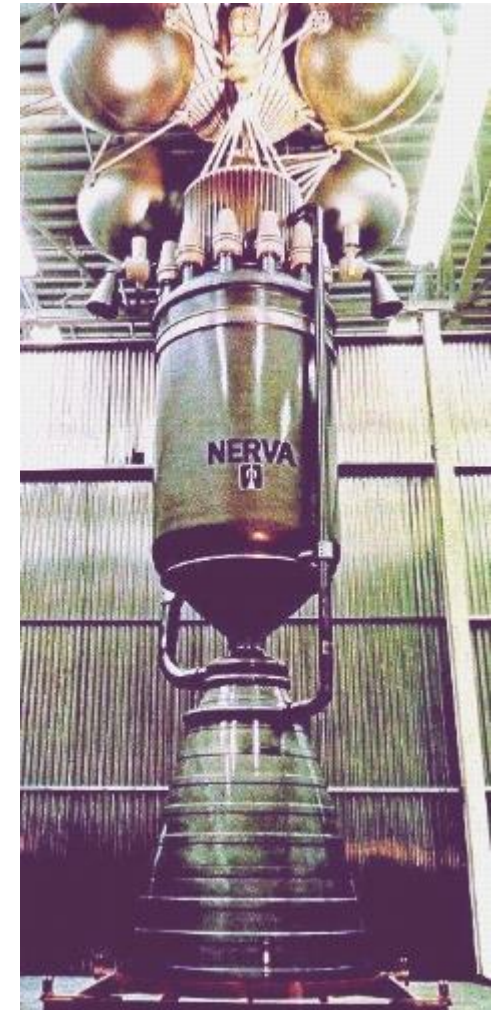


How Would Initial NTP Systems Work?

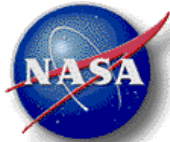
- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: $100,000 \text{ N} \approx 450 \text{ MW}_{\text{th}}$ at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O₂/H₂ engine actually runs hotter than NTP)



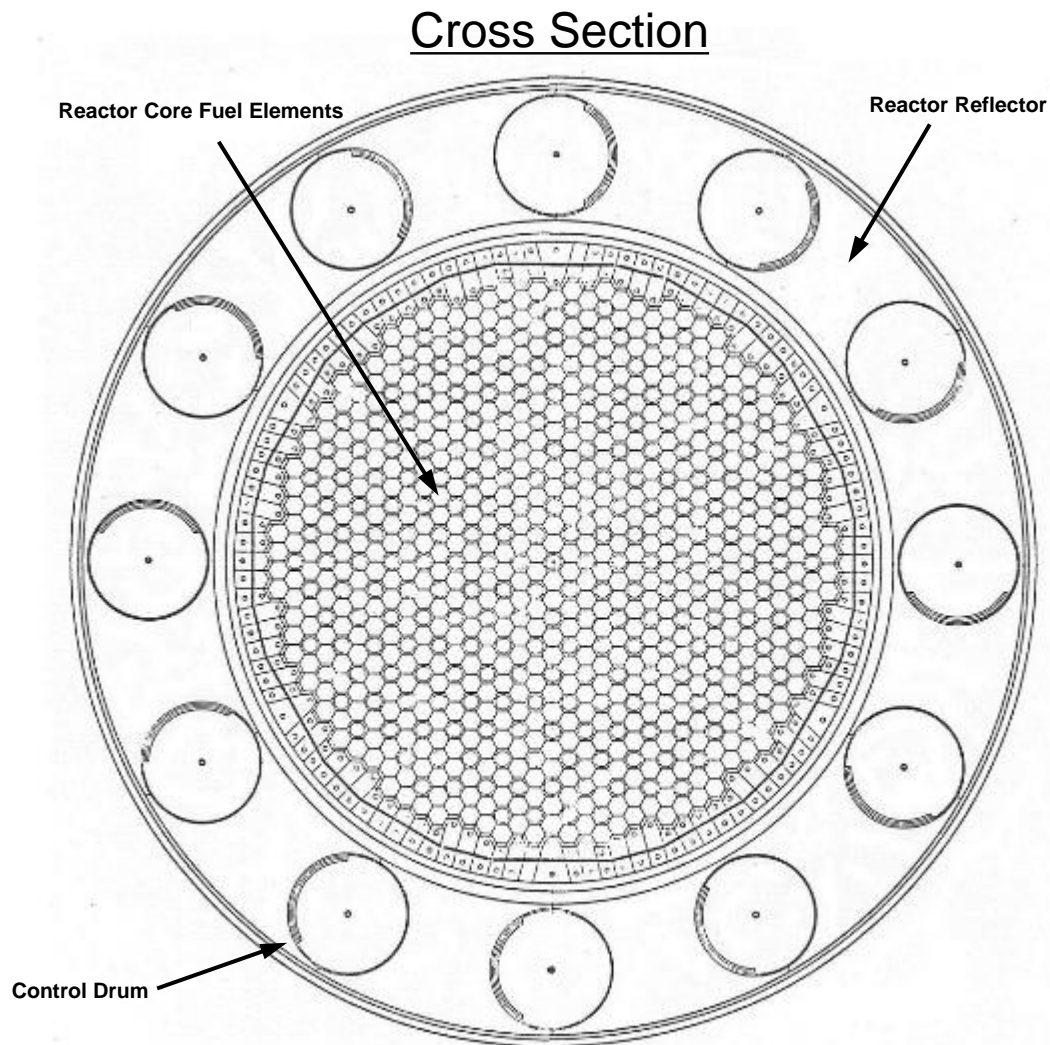
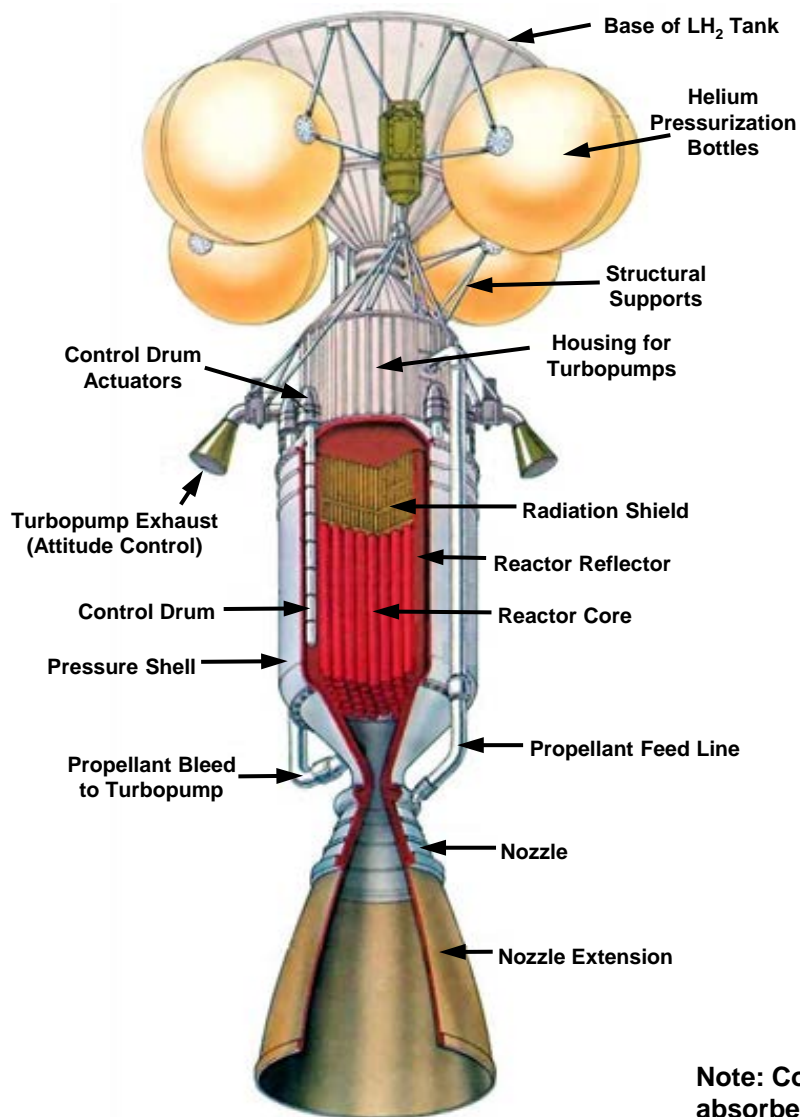
Major Elements of a Nuclear Thermal Rocket



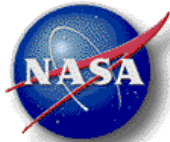
NERVA Nuclear Thermal Rocket Prototype



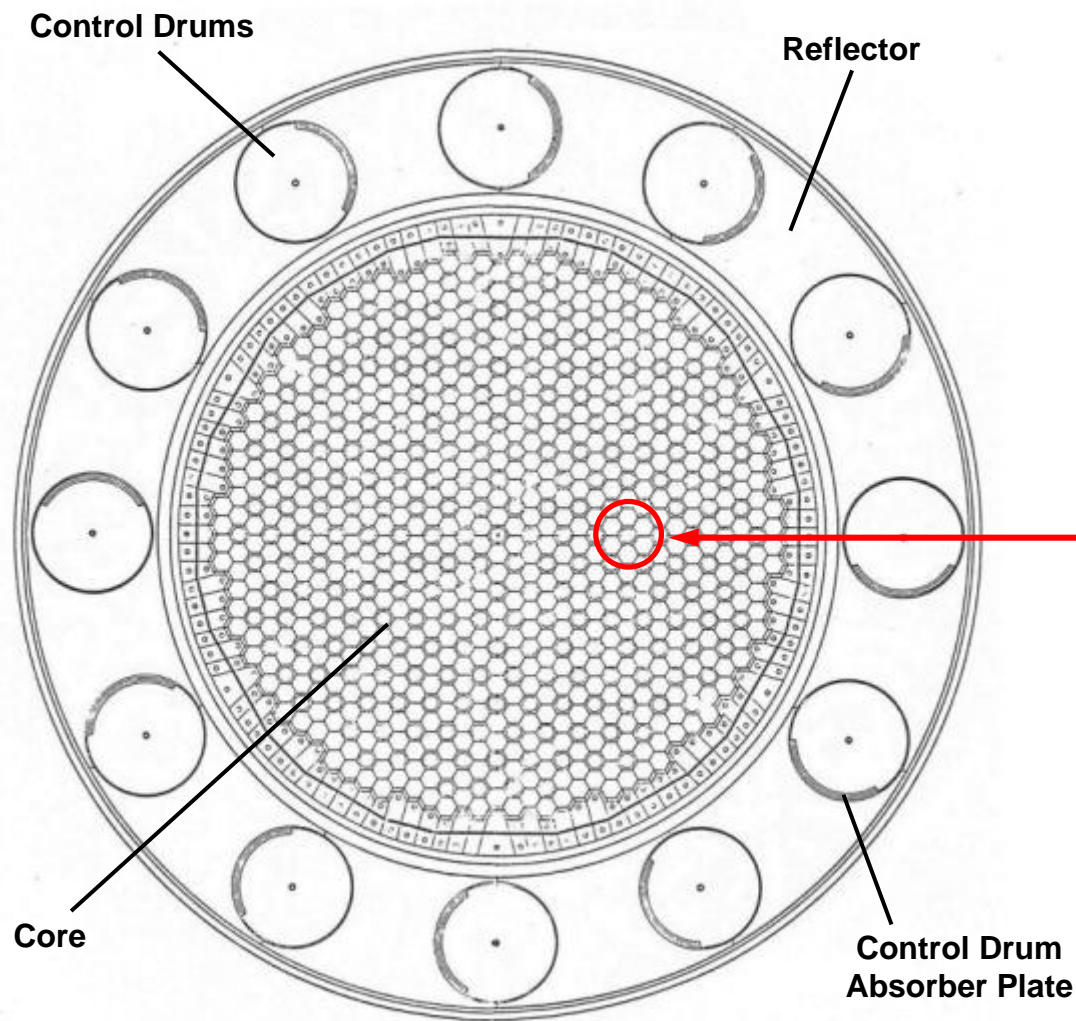
How Might Initial NTP Systems Work?



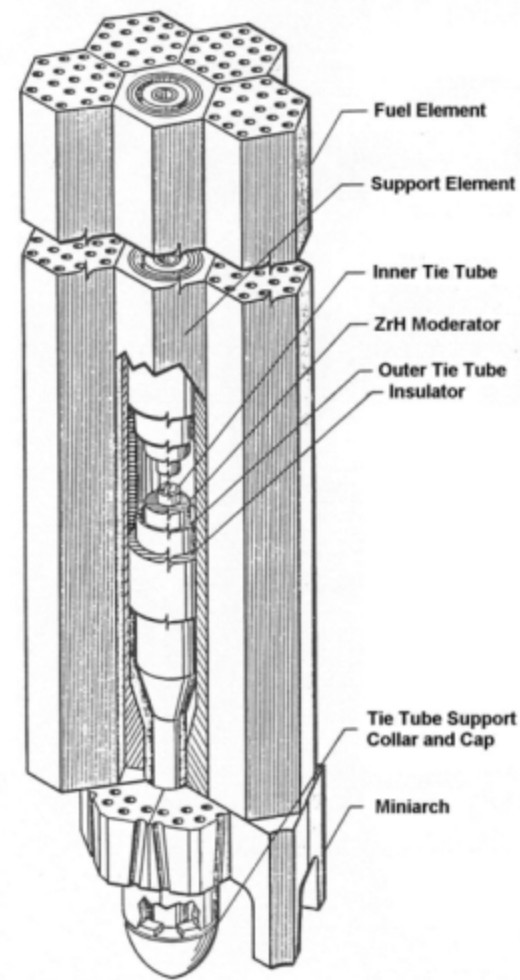
Note: Control drums rotate to control reactivity. Part of circumference covered with absorber and the rest is a reflector.



Previous NTP Engine Designs (Rover / NERVA)



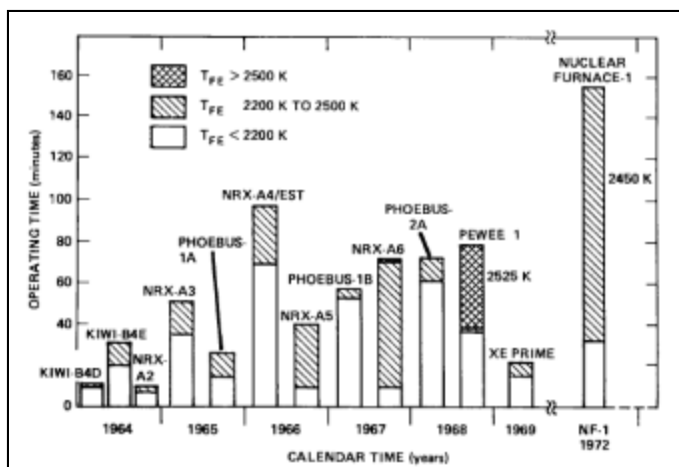
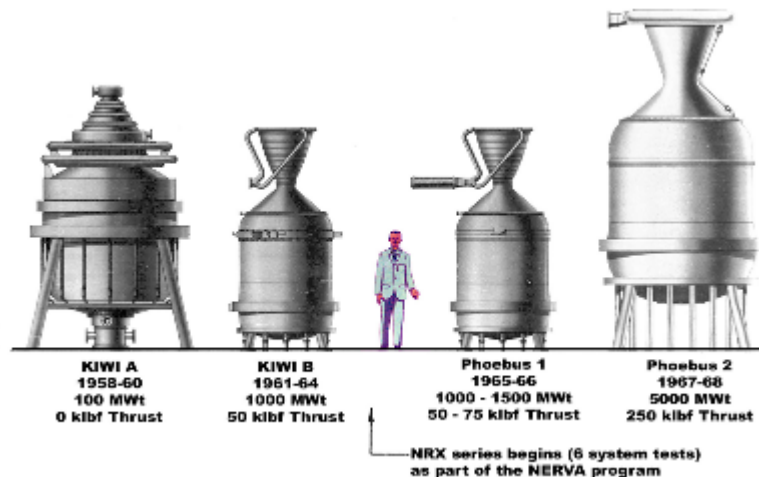
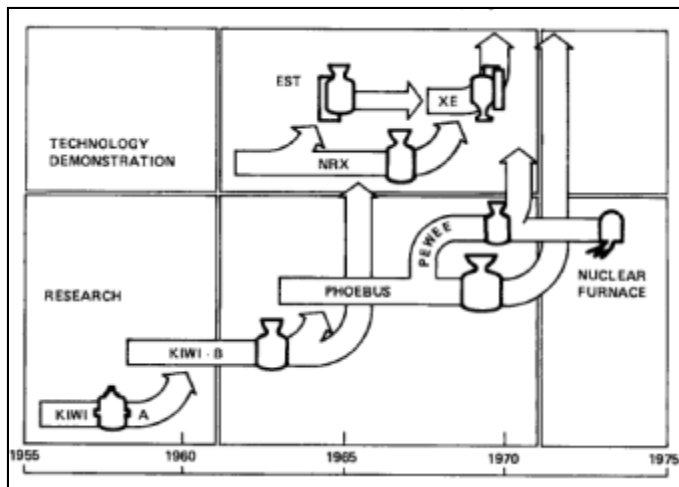
NERVA Reactor Cross Section

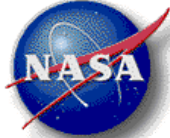


Fuel Segment Cluster



20 NTP Engines Designed, Built, and Tested During Rover/NERVA



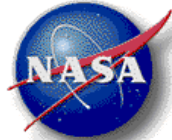


PHOEBUS 2A NUCLEAR ROCKET ENGINE

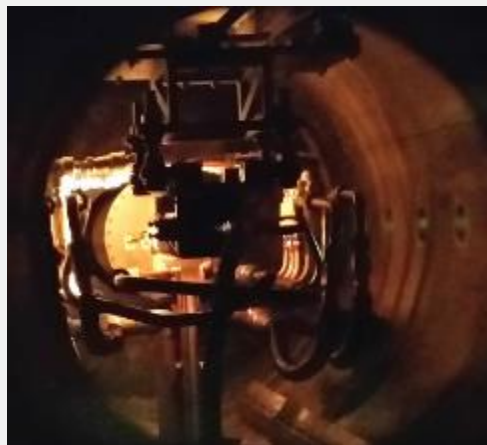


The most powerful nuclear rocket engine ever tested (Phoebus 2a) is shown during a high-power test. The reactor operated for about 32 minutes, 12 minutes at power levels of more than 4.0 million kilowatts.

NTP reference system is ~0.7 million kilowatts



Nuclear Thermal Rocket Element Environmental Simulator (NTREES) Test of ORNL Fuel Element to >2800 K



Left: John Warren and NTREES designer and lead engineer Bill Emrich watch Mike Schoenfeld (obscured) prepare for testing

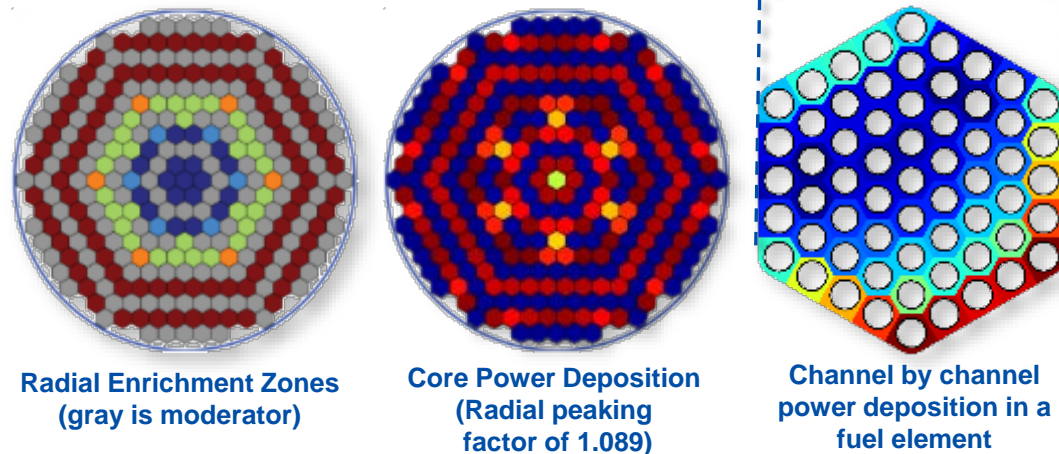
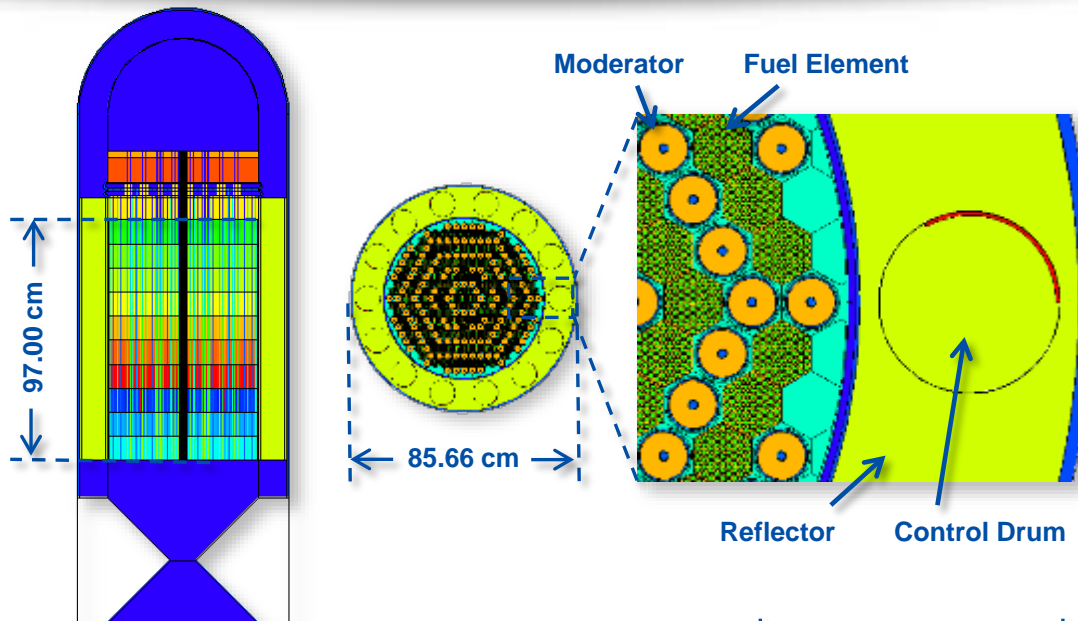


Monitoring testing



Space Capable Cryogenic Thermal Engine

(Baseball Card as of 5/12/15, Rev. 1.0.0)



General Description

SCCTE is a A LEU W-UO₂ cermet fuel, ZrH_{1.8} moderated nuclear thermal propulsion concept. SCCTE was produced with the Center for Space Nuclear Research's Space Propulsion Optimization Code (SPOC).

Reactor System Mass

Fuel Mass (151 Elements) (kg)	1029.8
Tie Tubes (150 Elements) (kg)	700.4
Radial Reflector + Control Drums (kg)	618.6
Axial Reflector (kg)	165.4
Barrel+Vessel+Other Core Structure (kg)	308.4
Total Mass (Excluding Shield) (kg)	2822.6

Key Performance Parameters

Nominal Isp (150:1 Nozzle)	896
Nominal Thrust (kN)	157.3 (~35k lbf)
Reactor Power (MW)	709.8
Fuel Temperature Max (K)	2850.0

Engine System Interface Information

Interface Point	Flow Rate (kg/s)	Pressure (MPa)	Temp. (K)
Core inlet	17.9	6.93	291
Core outlet	17.9	4.65	2698

Fuel Details

Fuel composition	W-UO ₂ -ThO ₂
Volume loading of Oxide (% vol.)	60.0
ThO ₂ in the Oxide (%mol.)	6.0
Enrichment of ¹⁸⁴ W (% atom)	98.0
Enrichment of ²³⁵ U (% atom)	19.75 to 13.13
Total Enriched W (kg)	376.0
Total ²³⁵ U (kg)	45.9
Percent Theoretical Density (% TD)	97.0

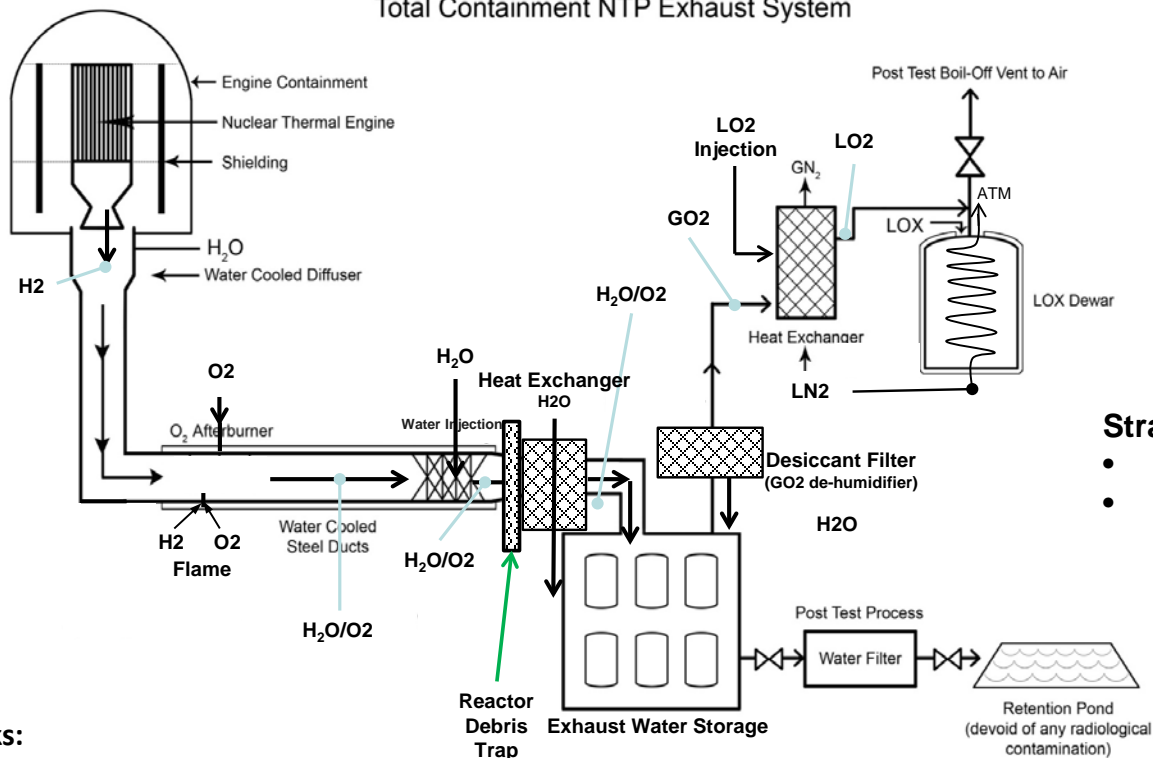


NTP Total Containment Test Facility Concept



Stennis Space Center

Total Containment NTP Exhaust System



Strategy:

- Fully Contain engine exhaust
- Slowly drain containment vessels after test

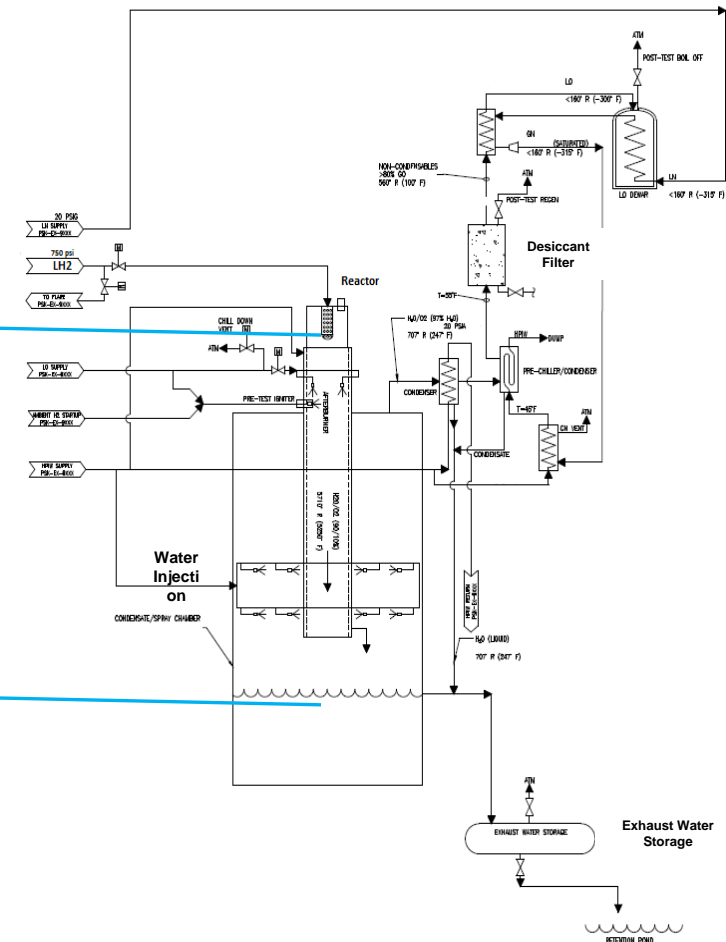
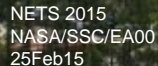
How it works:

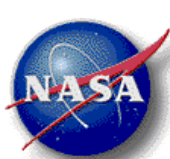
- Hot hydrogen exhaust from the NTP engine flows through a water cooled diffuser that transitions the flow from supersonic to subsonic to enable stable burning with injected LO2
 - Products include steam, excess O₂ and potentially, a small fraction of noble gases (e.g., xenon and krypton)
- Water spray and heat exchanger dissipates heat from steam/O₂/noble gas mixture to lower the temperature and condense steam
- Water tank farm collects H₂O and any radioactive particulates potentially present in flow.
 - Drainage is filtered post test.
- Heat exchanger-cools residual gases to LN₂ temperatures (freezes and collects noble gases) and condenses O₂.
 - LOX Dewar stores LO₂, to be drained post test via boil-off



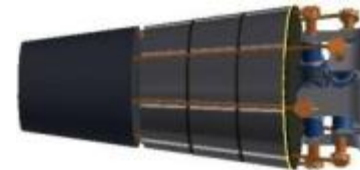
- Most of the infrastructure required by the NTP total containment ground test facility is already in place at A3:
 - Tower, test cell, propellant, HPIW & data and controls infrastructure, the Test Control Center, electric power, etc.
 - Major modifications, procurements, and construction work will be required and are captured in the ROM estimate.

SSC A3 Test Facility

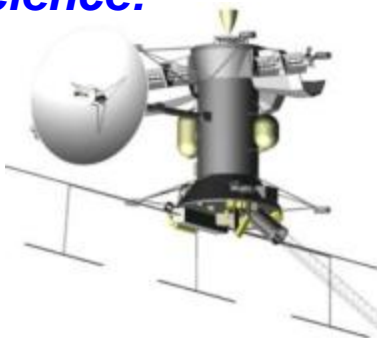




Safe, Compact, Near-Term Fission Power Systems Could Help Enable Higher Power Fission Propulsion Systems



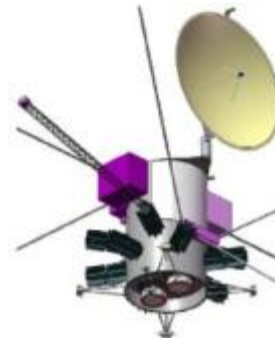
Science:



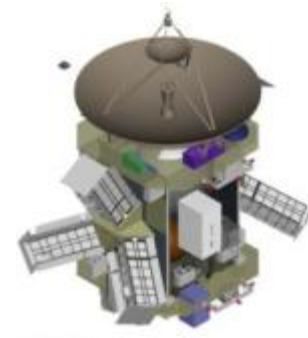
Jupiter Europa Orbiter
~600 We (5 to 6 RPS)



Neptune Systems Explorer
~3 kWe (9 Large RPS)



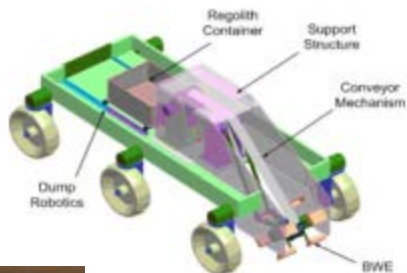
Kuiper Belt Object Orbiter
~4 kWe (9 Large RPS)



Trojan Tour
~800 We (6 RPS)

Exploration:

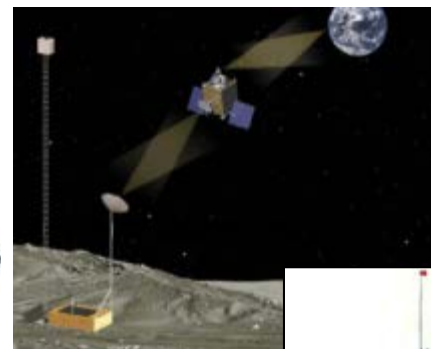
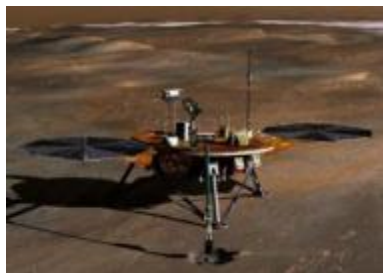
Teleoperated
Rovers



ISRU Demo
Plants



Site Survey
Landers



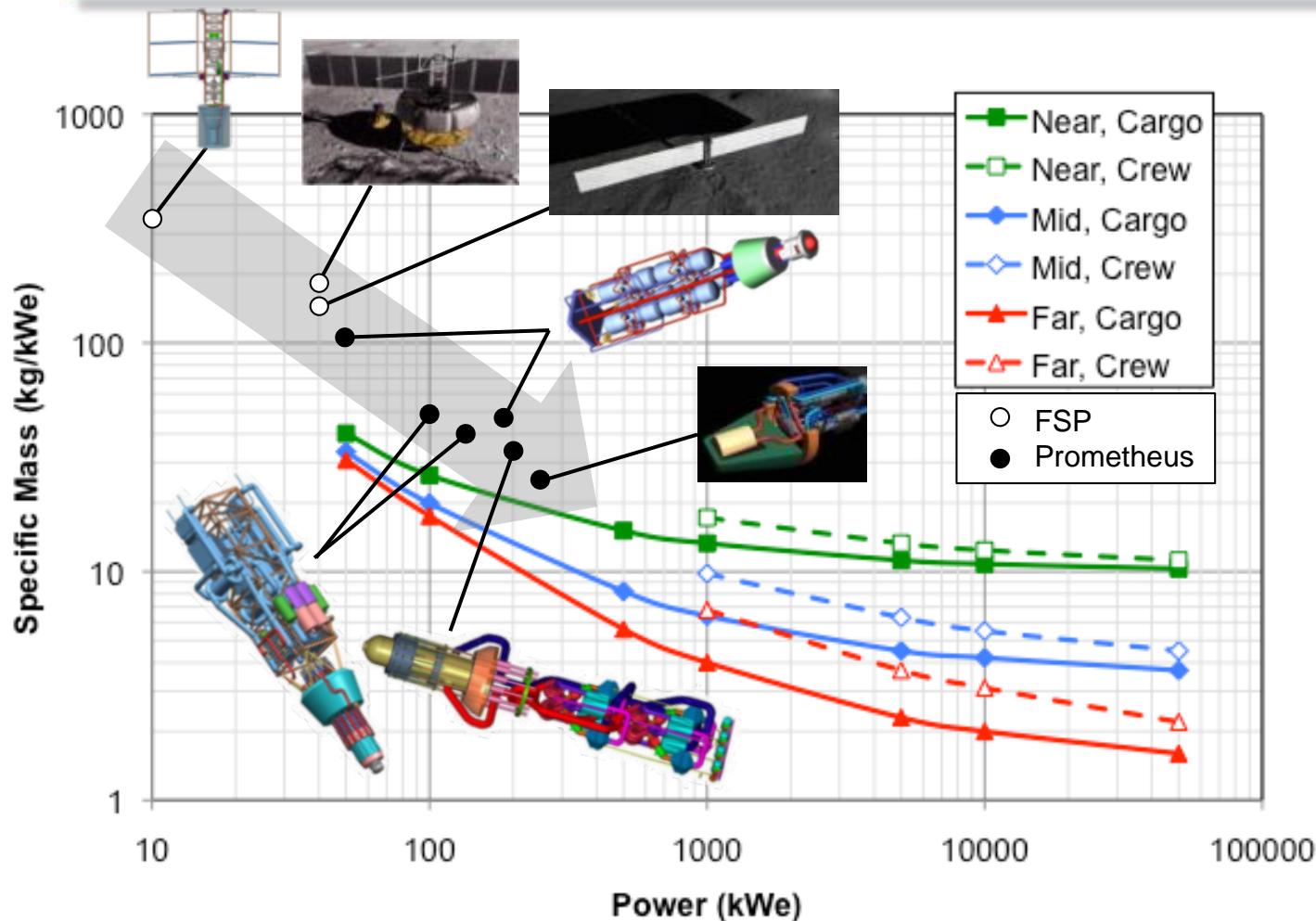
Comm Relay
Stations

Remote Science
Packages





Fission Can Provide the Energy for Either Nuclear Thermal or Nuclear Electric Propulsion Systems



Near=Liq Metal Rx, Brayton, 1300K, 6 kg/m², 200 Vac (Available ~10 yrs)
Mid=Liq Metal Rx, Brayton, 1500K, 3 kg/m², 1000 Vac (Available ~ 15-20 yrs)
Far=Liq Metal Rx, Brayton, 2000K, 1.5 kg/m², 5000 Vac (Available ~ 25-30 yrs)
Cargo=Instrument rated shielding, 1.6x10¹⁵ nvt, 1.2x10⁸ rad @ 2 m
Crew=Human rated shielding, 5 rem/yr @ 100 m, 7.5° half angle

- NEP Power System Performance Projections from 2001 STAIF Conference
- Fission Surface Power and Prometheus Concepts Superimposed

Chart courtesy
Lee Mason,
NASA GRC



Kilopower Technology Demonstration – Overall Objectives & Elements



- **Big Idea:**

- A compact, low cost, scalable fission power system for science and exploration

- **Innovation:**

- KiloPower: novel integration of available U235 fuel form, passive sodium heat pipes, and flight-ready Stirling convertors

- **Impact:**

- Provides Modular Option for HEOMD Mars Surface Missions
- Enables SMD Decadal Survey Missions
- Reduces NASA dependence on Pu238

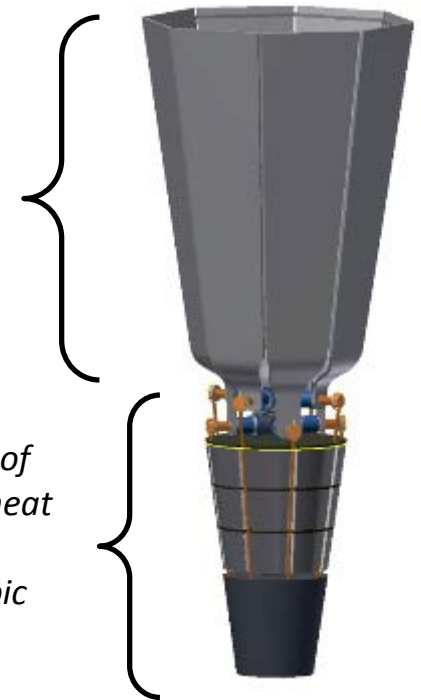
- **Goals:**

- **Nuclear-heated system-level test of prototype U-8Mo reactor core coupled to flight-like Stirling convertors**
- Detailed design concept that verifies scalability to 10 kW_e for Mars
- Prepare for flight test of titanium-water heat pipe radiator on ISS to verify Zero-G performance

1 to 10 kW_e Kilopower Technology

On-orbit test of variable conductance heat pipe radiator under steady-state & transient conditions

Full-scale nuclear test of reactor core, sodium heat pipes, and Stirling convertors at prototypic operating conditions



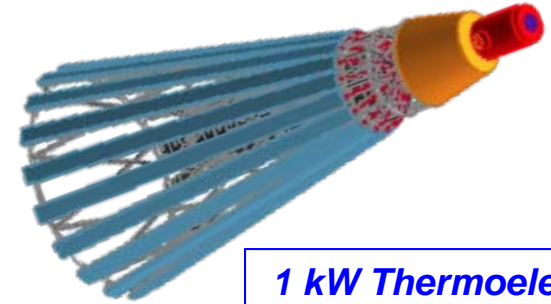
- **10X the power of current RPS**
- **Available component technologies**
- **Tested in existing facilities**



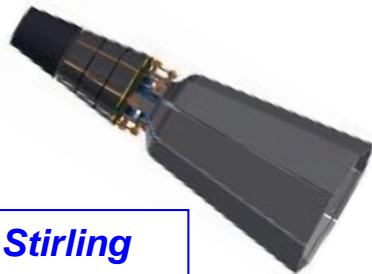
Kilopower-Enabled Concepts Family



- **Common Design Features include:**
 - 0.5 to 10 kWe; >10 year design life
 - Utilize available UMo reactor fuel from DOE-NNSA
 - Minimize thermal power to simplify reactor design and control
 - Incorporate passive Na heat pipes for reactor heat transport
 - Leverage power conversion technologies from RPS Program (TE, Stirling)
 - Design system so that it can be tested in existing DOE nuclear facilities

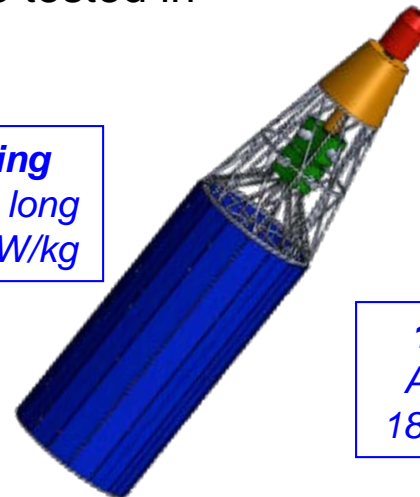


1 kW Thermoelectric
Approx. 4 m long
600 kg or 1.7 W/kg



800 W Stirling
Approx. 2.5 m long
400 kg or 2 W/kg

3 kW Stirling
Approx. 5 m long
750 kg or 4 W/kg



10 kW Stirling
Approx. 4 m tall
1800 kg or 5 W/kg



1 kWe-class Technology Demonstration establishes foundation for range of systems and capabilities



Kilopower Thermal Prototype



- **Kilopower Thermal Prototype is first of three steps to a nuclear ground demonstration**
 - Non-nuclear functional prototype with steel simulated reactor core
 - Non-nuclear prototype with depleted uranium simulated core
 - Nuclear demonstration with uranium reactor core
- **Thermal prototype validates core geometry and heat pipe attachment method prior to build of depleted uranium simulated core**
 - Steel core thermal properties are close enough to uranium to validate heat pipe attachment method under thermal load, and segmentation of core
 - First of two electrically heated trials of heat pipe attachment methods tested at temperature in vacuum



**Stainless Steel
Thermal Prototype**



Vacuum Tank Integration

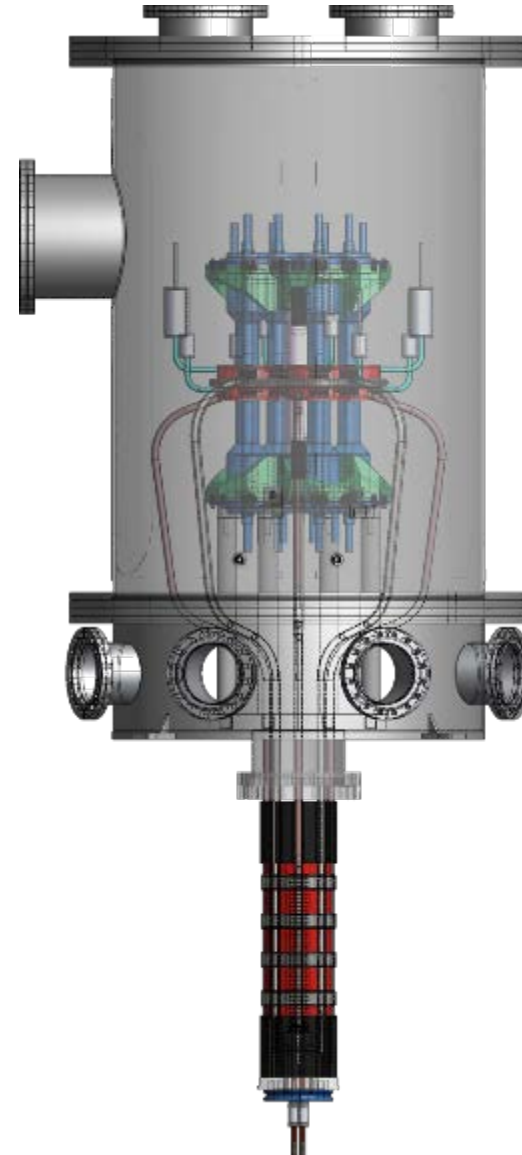
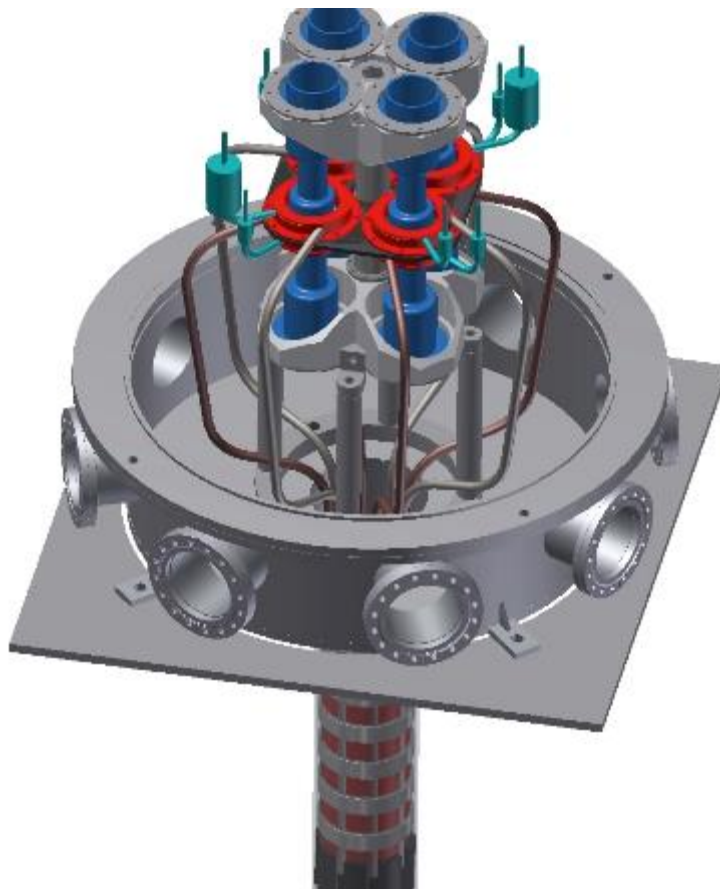


Integrated Assembly



Test

Latest Configuration of 1 kW_e Krusty Nuclear Demonstration

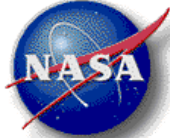




Partner Organizations Investing in Kilopower



- **DOE / National Nuclear Security Administration (NNSA)**
 - Nevada National Security Site Device Assembly Facility is being provided without cost to NASA
 - NNSA will own, keep, and dispose of Kilopower demonstration reactor core
 - *NNSA is contributing \$0.5M in FY16 and \$2M in FY17 to Kilopower*
- **HEOMD**
 - Significant interest from HAT for Evolvable Mars Campaign
 - Providing time of Human Spaceflight Architecture Team (HAT) members for Mars Kilopower Concept Development
 - Possible Kilopower use on 2024-26 Mars ISRU Surface Demo
- **Industry: Aerojet/Rocketdyne**
 - Committing Independent Research and Development funds in FY15 for reactor core materials research and testing
 - Interested in continued and broader partnership
- **Other Government Agencies: ARPA-E**
 - Contracts awarded for 1 kWe residential power: GENerators for Small Electrical and Thermal Systems (GENSETS)
 - Two Stirling technology contracts could have direct benefit to Kilopower

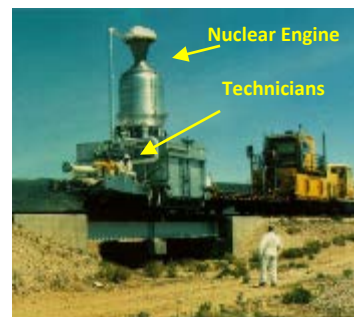


NTP Facts



- The volume of a toy marble could contain the mass of uranium providing the NTP energy for an entire human Mars mission

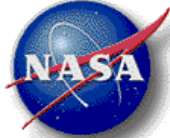
- Standing next to an NTP engine before launch for one year is less radiation than a diagnostic x-ray



=



- NTP ground test regulations allow the maximum annual public dose from NTP testing to be equivalent to ~20 hours of plane flight, which is also equivalent to ~25% of the natural radiation from food.



NTP Facts (Cont'd)

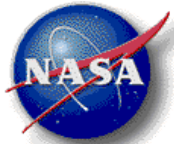


- Crews of nuclear submarines have lower radiation exposure than the general public above the water

- Using NTP for faster trip times to Mars exposes the astronauts to less galactic cosmic radiation



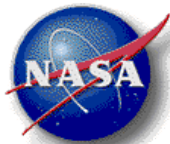
- NTP reactor fission products from the entire Mars mission is about equal to products formed after ~two weeks of runtime from a 10 MW college reactor



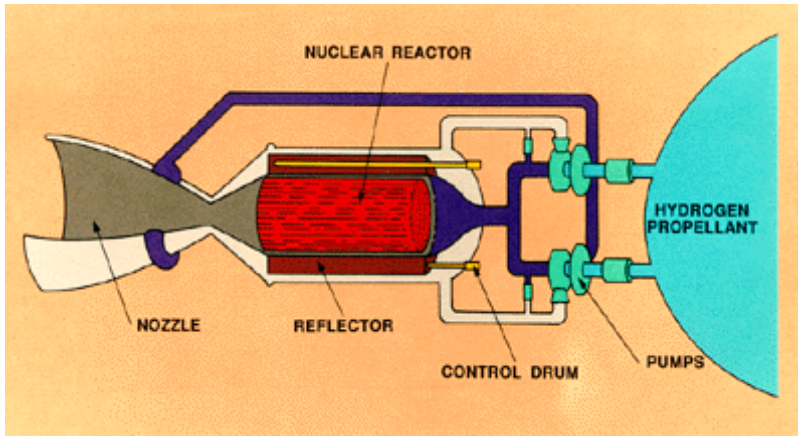
Deaths by TeraWatt Hours (TWh) *

Energy Source	Death Rate (per TWh)	Percent - World Energy /Electricity
Coal (electricity, heating, cooking)	100	26% / 50%
Coal (electricity -world average)	60	26% / 50%
Coal (electricity, heating, cooking) - China	170	
Coal (electricity) - China	90	
Coal - USA	15	
Oil	36	36%
Natural Gas	4	21%
Biofuel / Biomass	12	
Peat	12	
Solar (rooftop)	0.44	0.2% of world energy for all solar
Wind	0.15	1.6%
Hydro	0.10 (Europe death rate)	2.2%
Hydro (world including Banqiao dam failure)	1.4 (About 2500 TWh/yr and 171,000 Banquo dead)	
Nuclear	0.04	5.9%

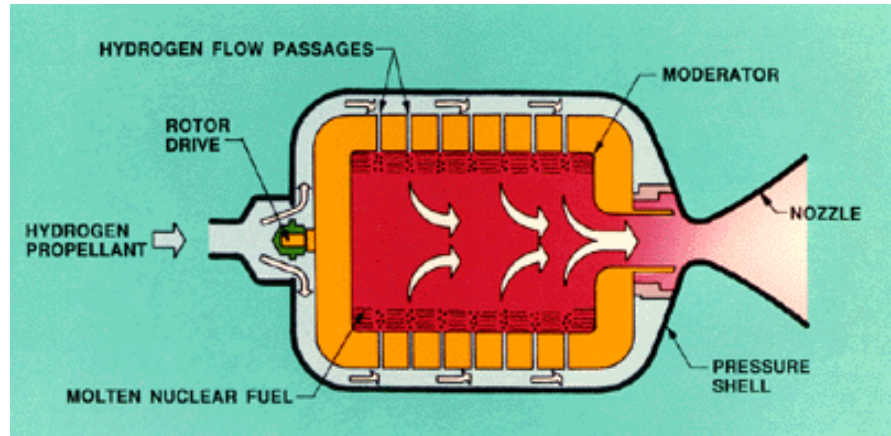
60% for coal for electricity, cooking and heating in China. Pollution is 30% from coal power plants in China for the particulates and 66% for sulfur dioxide. Mining accidents, transportation accidents are mostly from coal for electricity.



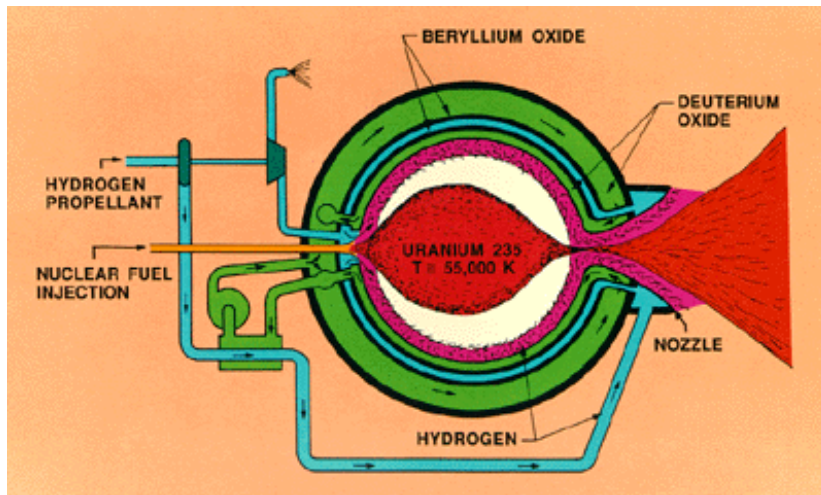
First Generation NTP Systems Could Help Enable Highly Advanced Propulsion Systems



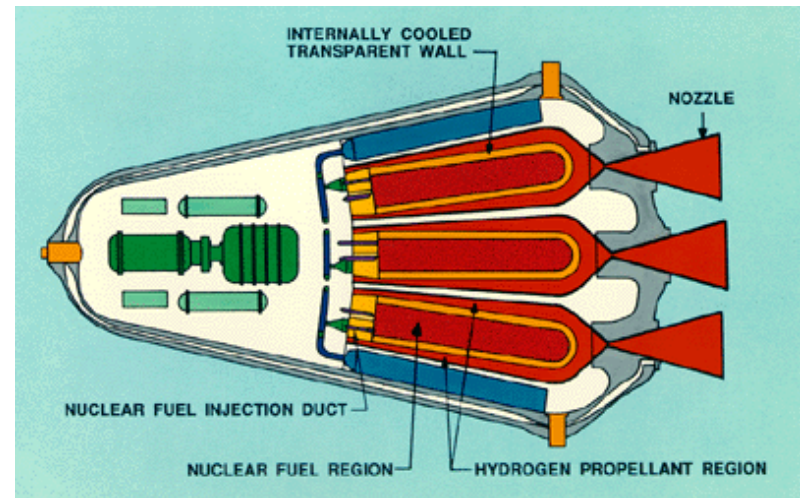
SOLID CORE NUCLEAR ROCKET



LIQUID CORE NUCLEAR ROCKET



Open-Cycle Gas Core Nuclear Rocket



Closed-Cycle Gas Core Nuclear Rocket



Future Plans / Path Forward

- Space fission power and propulsion systems have the potential to enable ambitious missions throughout the solar system.
- Space fission power and propulsion will only be utilized if affordable and viable development strategies can be devised.
- Ongoing projects are focused on developing and demonstrating those strategies.